TITLE: Visual and Vestibular Determinants of Perceived Eye-Level

Visual and Vestibular Determinants of Perceived Eye-Level

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Summary

Both gravitational and optical sources of stimulation combine to determine the perceived elevations of visual targets. The ways in which these sources of stimulation combine with one another in operational aeronautical environments are critical for pilots to make accurate judgments of the relative altitudes of other aircraft and of their own altitude relative to the terrain. In a recent study (Cohen, Stoper, Welch, & DeRoshia, 2001), my colleagues and I required eighteen observers to set visual targets at their apparent horizon while they experienced various levels of G_Z in the human centrifuge at NASA-Ames Research Center. The targets were viewed in darkness and also against specific background optical arrays that were oriented at various angles with respect to the vertical; target settings were lowered as G_Z was increased; this effect was reduced when the background optical array was visible. Also, target settings were displaced in the direction that the background optical array was pitched. Our results were attributed to the combined influences of otolith-oculomotor mechanisms that underlie the elevator illusion and visual-oculomotor mechanisms (optostatic responses) that underlie the perceptual effects of viewing pitched optical arrays that comprise the background. In this paper, I present a mathematical model that describes the independent and combined effects of *G_Z intensity* and the *orientation* and *structure* of background optical arrays; the model predicts quantitative deviations from normal accurate perceptions of target localization under a variety of conditions. Our earlier experimental results and the mathematical model are described in some detail, and the effects of viewing specific optical arrays under various gravitational-inertial conditions encountered in aeronautical environments are discussed.

Introduction

The perceived locations of visual targets depend on both retinal and extra-retinal sources of information (Bell, 1823; Helmholtz, 1866; Hering, 1879; Wade, 1978). The retinal information is derived from the images of the targets on the retina, their locations on the retina, and the shapes, locations, and orientations of images from other objects in the visual field, particularly those that comprise the background optical array against which the target objects are viewed. The extra-retinal information is derived from the position of the eyes relative to the head, and of the head relative to a specific external frame of reference, such as that provided by gravity. When the relationship between an observer and the gravitational frame of reference is altered, as when the observer is tilted with respect to gravity, or when the magnitude or direction of the gravitational-inertial force (GIF) is altered, as often occurs in accelerating aircraft or spacecraft, the apparent locations of seen objects are usually altered as well.

Two illusions, the oculogravic illusion and the elevator illusion are extremely common (and often go unrecognized) in operational aviation environments. These illusions cause errors in the perceived locations of visual targets that are viewed by observers in accelerating vehicles (Cohen, 1973; Cohen, Crosbie, & Blackburn, 1973; Graybiel, 1952; Schöne, 1963; Whiteside, Graybiel & Niven, 1965). The oculogravic illusion results when an observer is exposed to a change in both the direction and the magnitude of the GIF acting on his/her body, as when an airplane is accelerating, decelerating, or is in an uncoordinated turn. In this illusion, the observer experiences not only a change in the apparent location of isolated visual targets, but a change in the apparent orientation of the surrounding visual array as well. In contrast, the elevator illusion results when an observer is exposed to a change in the magnitude, but *not* the direction, of the GIF, as can occur in parabolic flight or in a coordinated turn. In this illusion, an isolated visual target appears to be above its true location when viewed in hypergravity (where the illusion is also often referred to as the *G-excess effect*), and below its true location when viewed in hypogravity (where the illusion has been called the *oculo-agravic illusion*). The elevator illusion is greatly attenuated when the target is viewed in the presence of a structured visual array (DiZio, Li, Lackner & Matin, 1997; Schöne, 1963), but specific quantitative data regarding the amount of attenuation as a function of optical structure had not been reported until just last year (Cohen et al., 2001). The

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elevator illusion has been attributed to changes in oculomotor control that result from atypical stimulation of the otolith organs under altered gravitational-inertial conditions (Cohen, 1973; 1992; 1996).

Altered gravitational-inertial conditions are not the only means by which changes in the apparent locations of visual targets can be brought about; changes in the orientation of the visual background against which a target is viewed can have similar effects. When a background optical array is not aligned with the observer's body, for example when the array is pitched, i.e., rotated up or down about an observer's left-right body axis, it can produce dramatic illusory changes in the apparent elevation, or height, of a visual target. The array can be comprised of a small box (Cohen, Ebenholtz & Linder, 1995; Kleinhans, 1970; Stoper & Cohen, 1989; 1991), an entire room (Cohen et al., 1995; Matin & Fox, 1989), or even individual tilted lines (DiZio et al., 1997; Matin & Li, 1992; 1994). In the aviation setting, these effects can result from viewing sloping terrain or banks of clouds.

Clearly, these illusions can lead to disorientation in flight when pilots do not attend to their instruments and rely instead on physiological stimulation provided by their visual and vestibular systems. The current paper represents a first-order attempt to model the effects of altered visual and vestibular stimulation as they affect the spatial localization of simple visual targets. This particular modeling attempt is restricted to acceleration conditions in which the magnitude, but not the direction, of the GIF is altered (i.e., conditions that lead to the elevator illusion rather than oculogravic illusion).

In the study by Cohen et al. (2001), we evaluated the relative contributions of retinal and extra-retinal information on localizing a visual target by systematically altering: 1) the orientation of the optical array, 2) the structure of the array, and 3) the intensity of the GIF. Observers were exposed to various combinations of these variables while they adjusted the position of a target so that it appeared to be at their horizon. The data from this study provide the basis for the model reported here.

Description of the Study

Observers **-** Eighteen observers signed a document indicating informed consent, were screened for tolerance to acceleration on the centrifuge by demonstrating their ability to undergo more than five minutes of continuous exposure to 2.0 G_Z without performing any straining maneuvers and without experiencing any difficulties, and were determined to have 20/30 vision or better, either uncorrected or as corrected by eyeglasses or contact lenses.

Apparatus **-** Each observer was seated on a freely swinging chair that faced radially outward in the darkened gondola of the human-rated centrifuge at Ames Research Center. The chair was individually balanced for each observer to assure that the GIF was increased exclusively along the **z** (head to foot) body axis, as verified by a tri-axial accelerometer mounted on the chair at the level of the observer's ears.

A tightly fitting helmet, rigidly attached to the chair, stabilized the position of the observer's head so that the eyes were centered with respect to an adjustable box (background array) that could be pitched towards or away from the observer by $\pm 20^{o}$. The interior of the box was covered on all surfaces with 10-to-the-inch graph paper that was aligned with the edges of the box, and the box was fitted with eight electro-luminescent strips that defined the eight interior edges. Thus, the illuminated edges were the four that defined the rectangular distal surface, and the four that protruded from the corners of this surface towards the observer along the outer edges of the floor and the ceiling of the box; the four edges closest to the observer at the open end of the box were not illuminated. The electro-luminescent strips provided the sole source of illumination to the box.

When viewed at the rear of the box, the vertical electro-luminescent lines subtended about 45^{o} visual angle from top to bottom, and were laterally separated by approximately 31^{o}. A light-emitting diode (LED) was mounted in a track that ran from the top to the bottom of the box along the center of its rear wall. An electric motor controlled the vertical position of the LED in its track, and another motor adjusted the pitch orientation of the box.

Experimental Design **-** The experiment consisted of 27 test conditions that were derived by combining three conditions of optical structure with three orientations of the box and three intensities of GIF. The conditions were: *Optical structure* - 1) the box was brightly illuminated, and all interior details, as well as the LED target, were fully visible, 2) the box was dimly illuminated by the electro-luminescent strips that defined its interior edges; the observers reported that only the strips and the LED target were visible, and 3) the box was dark, except for illumination of the LED target itself. *Orientation* - 1) the box was pitched up 20^{o} (i.e., top towards observer), 2) the box was level, and 3) the box was pitched down 20^{o}. *GIF* - 1) the centrifuge provided 1.003 G_Z (nominally, 1.0 G_Z), 2) the centrifuge provided 1.5 G_Z, and 3) the centrifuge provided 2.0 G_Z at the observer's head.

The experimental conditions of optical structure and orientation were counterbalanced across observers, and the sequence of GIFs within each session was determined by a Latin-square design.

Data Collection **-** Experimental data were fed from the centrifuge gondola via slip-rings to a digital computer, and data collection was initiated no sooner than one minute after the centrifuge had achieved the desired steady-state G_Z. The experimenter set the target near the top or bottom of the box on

alternating trials, and the observers adjusted the position of the target until it appeared to be at their horizon; the observers then pressed a button, and the location of the target was automatically registered. The experimenter repositioned the target, and the observers again attempted to place it at their horizon. The experimenter set the box at a new orientation, and the procedure was repeated until four settings to apparent eye level were obtained from each observer at each of the three box orientations. All viewing was binocular. Whenever the experimenter adjusted the position of the target or the orientation of the box, the observers closed their eyes.

Summary of Results **-** As verified by ANOVA and regression analyses, the settings of the target were progressively lowered as the magnitude of the GIF was increased. Thus, a target that remained at true eye level would appear to be progressively more elevated with increased G_Z. Similarly, the settings of the target varied with the orientation of the background optical array (box) in which the target was viewed; the settings were biased in the same direction as that in which the array was pitched. Thus, a target at true eye level would appear to be higher when the array was pitched down, and lower when the array was pitched up. The optical structure of the array also influenced settings of the target. Overall, the settings made in the dark tended to be lower (because the effects of increased G_Z were not attenuated) than those made either when the dimly illuminated electro-luminescent strips or the fully illuminated box defined the background array (where the effects of increased G_Z were attenuated). The effects of optical structure significantly interacted with both the effects of G_Z and those of array orientation. Thus, optical structure was shown to have two independent qualities: 1) it allows a tilted visual array to bias perception in the same direction as the array is pitched, and 2) it inhibits a change in the strength of the GIF from biasing perception. The data of this study are depicted in Figure #1.

Development of the Current Model

Variables

The study described above (Cohen et al., 2001) provides a clear picture of the critical stimuli, and the likely mechanisms that subserve the perception of target elevation. Three distinct underlying variables emerge from that study:

Variable 1 **–** The data illustrate a general effect of the intensity of the GIF on the perceived elevation of the target. This effect occurred both in the dark and with all of the background optical arrays used in the study. Based on the data shown in Figure #1, this effect is a linear function of the intensity of the GIF under each of the conditions tested, although the slope of the function differs for the different arrays. In previous studies (e.g., Cohen, 1973), this effect was termed the "elevator illusion," and its underlying mechanism is considered to be a change in stimulation of the otolith organs, resulting in an otolith-oculomotor drive that changes the registered position of the eyes in the head (Cohen, 1996).

Variable 2 **–** The data indicate an effect of the orientation of the optical array on the perceived elevation of the target. This effect occurred whenever the background optical array was visible, but because it was extremely small in the dark (only 0.04^o/degree), and was virtually constant in the light ($.45^o$ to $.46^o$/degree) at all levels of GIF tested, it was shown to depend only on the structure and the orientation of the optical array, but to be independent of the GIF. In previous studies (e.g., Cohen et al., 1995; Stoper & Cohen, 1989; 1991; Matin & Fox, 1989; Matin & Li, 1992), this effect was referred to as "visual capture," and it is considered to be due to an optostatic drive that independently changes the registered position of the eyes in the head (Crone, 1975; Cohen et al., 1995).

Variable 3 **–** Because the effects of increased GIF depended on the structure of the background visual array, the data suggest a separate retinal mechanism to suppress the otolith-oculomotor drive in the presence of such an array. (As was shown, with a dark background, the apparent elevation of the target changed at a mean rate of 9.41^o per G_Z; when the array was comprised of dimly lit electro-luminescent strips, which provided additional optical structure, this effect was reduced to 4.44^o per G_Z, a reduction of 53%; when the array was a fully illuminated box, providing rich optical structure, the effect measured 3.30^o per G_Z, a reduction of 65%.) The otolith-oculomotor drive to be suppressed by the retinal structure of the array varies with the intensity of the GIF. Thus, attenuation of the otolith-oculomotor drive is jointly affected by the intensity of the GIF and by the structure of the optical array.

Combined Action of Variables

A simple multiple regression analyses of the data from Cohen et al. (2001) was used to generate the linear model presented here. The regression analysis suggests four separate parameters that combine to account for the individual and interactive effects of visual and vestibular stimulation in the localization of visual targets. These parameters are:

A. A **fixed constant** that is given by idiosyncratic factors determined by the individual subjects, and specific viewing conditions. This constant provides the zero intercept for the model, and

indicates where a target would be positioned when all of the other parameters are reduced to zero, i.e., when a target is viewed in the absence of gravity and in the absence of any background optical array. This constant, designated as ***b*** in the current model, indicates that the perceived elevation of a single target viewed in the dark and in the absence of gravity would be 4.36^{o} below the objective level of the eyes.

B. An **otolith-oculomotor drive** that is caused by altered stimulation of the otolith organs as a result of exposure to increased GIFs; the values for this variable are directly proportional to the intensity of the GIF acting on the observer. This term is given by $\underline{\alpha * (g)}$, where α is a proportionality constant that reflects the effectiveness of otolith organ stimulation, and *g* is the intensity of the GIF in units of G_Z. For a single target viewed in an otherwise totally dark environment, this parameter causes the target to appear progressively more elevated at a rate of 7.67^{o} for every 1.0 G_Z increment.

C. A **retinal-oculomotor drive** that is given by the orientation of the background optical array, weighted by the amount of optical structure in the array. The best estimate for the weighting of this mechanism is given by the empirically determined slope of the change in target settings relative to the change in orientation of the optical array. This term is given by $\underline{\beta * (o \ x \ os)}$, where β is a proportionality constant that reflects the relative amount by which the oculomotor drive is activated by the product of *orientation x optical structure*. For the target in the dark, the background pitch orientation values of -20^{o}, 0^{o} and $+20^{o}$ are multiplied by the empirically-determined slope of $.04^{o}$ per degree; for those conditions where the background optical array was visible, the pitch orientation values of -20^{o}, 0^{o} and $+20^{o}$ are multiplied by the empirically-determined slope of $.46^{o}$ per degree. These products are then incorporated into the multiple linear regression model, which yields a value of 0.99 for the β coefficient.

D. A **Retinal suppression of the otolith-oculomotor drive**, which results from the property of optical structure in the background array to suppress the effects of the GIF. Since the amount of suppression differs with both the intensity of the GIF and the optical structure of the background array, this parameter is given by $\underline{\gamma * (g \ x \ sp)}$, where γ is a proportionality constant, *g* is the intensity of the GIF applied along the z axis, and *sp* is the relative ability of the background array to suppress the effects of the GIF. As empirically determined, this parameter takes on the values of 0 (i.e., no suppression) for an unstructured optical array (in the dark), .53 suppression with the background dimly illuminated, and .65 suppression with the full grid visible. Since the stimulus to be suppressed is directly proportional to the intensity of the GIF, the values for this parameter are 0 at all levels of G_Z in the dark, .53, .795, and 1.06 at 1.0, 1.5 and 2.0 G_Z, respectively, with the background array comprised of strips, and .65, .975, and 1.3 at 1.0, 1.5 and 2.0 G_Z, respectively, with the full optical array. The value of the constant, γ, is 4.97.

Thus, as shown in Table #1, the complete model is summarized as follows:

$$Target\ Setting = \alpha *(g) + \beta *(o \ x \ os) + \gamma *(g \ x \ sp) + b$$

Where: $\alpha *(g)$ represents the effects of the otolith-oculomotor drive due to changes of the GIF; $\beta *(o \ x \ os)$ specifies the retinal-oculomotor drive, due to the orientation and optical structure of the background; $\gamma *(g \ x \ sp)$ designates the suppression of the otolith-oculomotor drive, which depends on the structure of the optical array and the intensity of the GIF, and *b* represents the zero intercept that would result in the absence of both gravity and background optical structure. A plot of the empirical data from the study (Cohen et al., 2001), compared with those generated by the model, is shown in Figure #2. Although the present model accounts for the experimental data extremely well, applying these modeling effects to more operationally realistic settings is probably quite a different matter.

Limitations of the Current Model

The model presented here is obviously limited to those conditions where the GIF is systematically manipulated in magnitude alone, and where its direction is unchanged; also the specification of the background optical array is highly restricted in the experimental study from which the model is derived. Clearly, the current model reflects a work in process. Nevertheless, the model constitutes a starting point from which additional variables can be explored. The addition of terms for somesthetic components and for dealing with changes in the direction as well as the magnitude of altered GIFs are conceptually feasible, and extended modeling efforts regarding spatial orientation under a wide range of more operationally realistic conditions can ultimately be accomplished. As long as disorientation in flight

remains an operational problem, any attempts to extend our understanding of these issues are probably quite worthwhile.

Unfortunately, the expansion and further application of the model to more operationally realistic settings must await future investigations.

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Figure #1

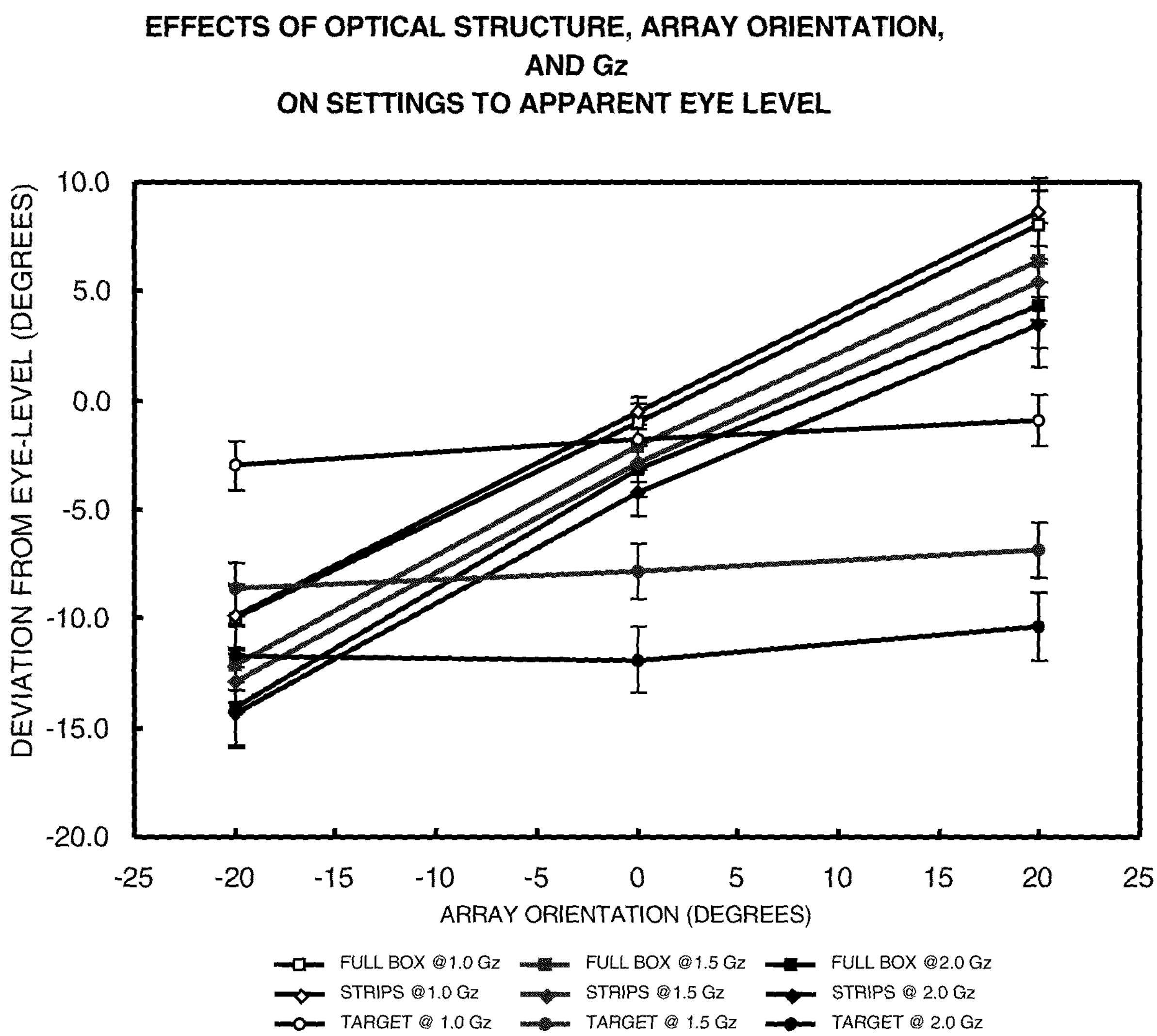

EFFECTS OF OPTICAL STRUCTURE, ARRAY ORIENTATION, AND Gz ON SETTINGS TO APPARENT EYE LEVEL
DEVIATION FROM EYE-LEVEL (DEGREES)
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25
-20
-15
-10
-5
0
5
10
15
20
25
ARRAY ORIENTATION (DEGREES)
FULL BOX @1.0 Gz
FULL BOX @1.5 Gz
FULL BOX @2.0 Gz
STRIPS @1.0 Gz
STRIPS @1.5 Gz
STRIPS @ 2.0 Gz
TARGET @ 1.0 Gz
TARGET @ 1.5 Gz
TARGET @ 2.0 Gz

Table #1

SUMMARY OUTPUT OF FULL REGRESSION ANALYSIS OF MODEL RESULTS

$$Target\ Setting = \alpha * (g) + \beta * (o\ x\ os) + \gamma * (g\ x\ sp) + b$$

Regression Statistics

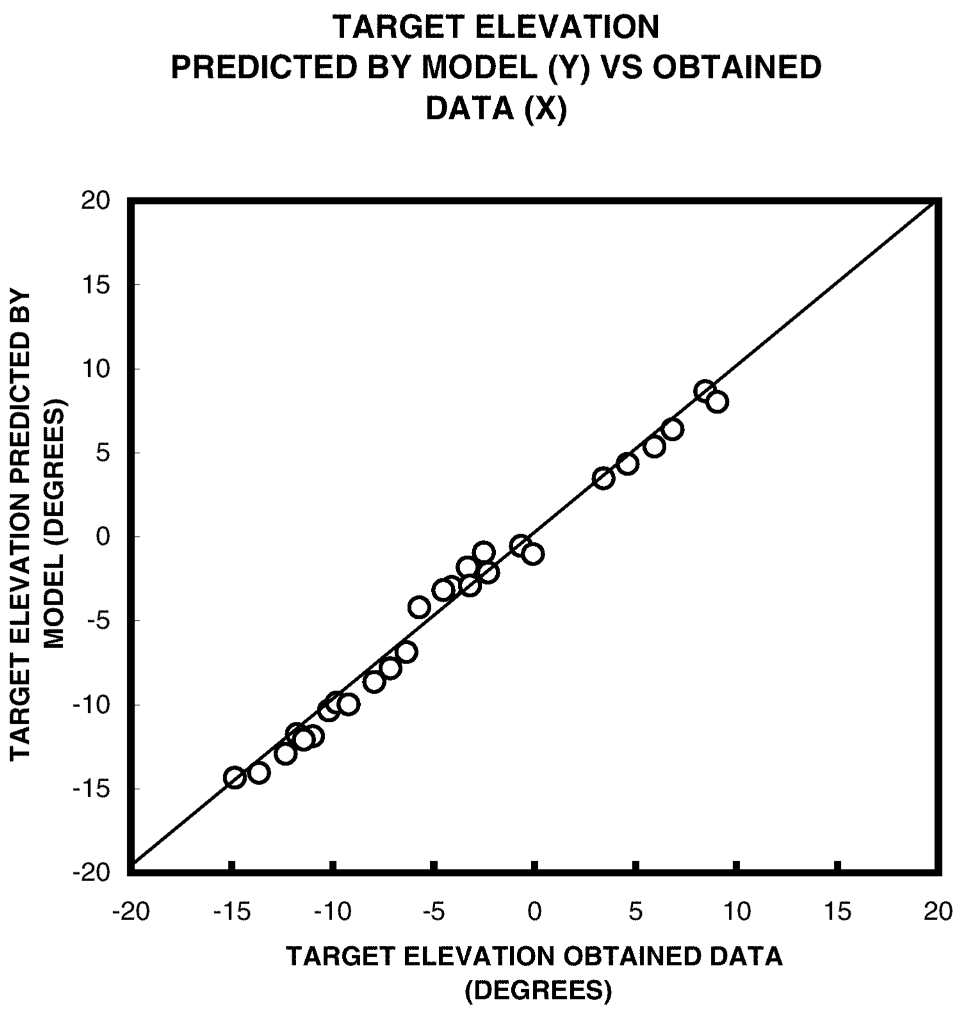
Multiple R	0.994
R^2	0.987
Adjusted R^2	0.986
Standard Error	0.849
Observations	27

ANOVA

	df	SS	MS	F	Significance F
Regression	3	1280.36	426.79	592.14	6.61E-22
Residual	23	16.58	0.72		
Total	26	1296.94			

Model Parameter	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	4.36	0.62	7.00	3.88E-07	3.07	5.64
Otolith-Oculomotor Drive	-7.67	0.43	-18.00	4.73E-15	-8.55	-6.79
Retinal-Oculomotor Drive	0.99	0.03	37.34	4.35E-22	0.94	1.05
Retinal Suppression of Otolith-Oculomotor Drive	4.97	0.37	13.35	2.55E-12	4.20	5.74

Figure #2


TARGET ELEVATION
PREDICTED BY MODEL (Y) VS OBTAINED
DATA (X)
TARGET ELEVATION PREDICTED BY
MODEL (DEGREES)
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20
TARGET ELEVATION OBTAINED DATA
(DEGREES)